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Constraining SUSY Models with Spontaneous CP-Violation via $B \to \psi K_s$

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Abstract

We study CP-violating effects in $B \to \psi K_s$ decay within minimal supersymmetric models with spontaneous CP-violation. We find that the CP-asymmetry predicted by the Standard Model in this decay, $\sin 2\beta \geq 0.4$, cannot be accommodated in these models without violating the bound on the neutron electric dipole moment. This result holds for NMSSM-like models with an arbitrary number of sterile superfields. Further implications of the scenario are discussed.

1 Introduction

The origin of CP-violation is one of the most profound problems in particle physics. In the Standard Model, all observable CP-violating effects in the kaon system can be successfully explained via the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [1]. However, the physical principles lying behind CP-violation are still not understood.

One of the more elegant approaches to the problem of CP-violation is based on the possibility of spontaneous T-breaking in multi Higgs doublet systems [2]. Supersymmetric models can provide such systems and thus are a natural setting to implement this idea. Spontaneous CP-violation (SCPV) in susy models has drawn considerable attention [5-10] due to the following attractive features:

- CP-phases become dynamical variables,
- CP-symmetry is restored at high energies,
- it allows to avoid excessive CP-violation inherent in susy models.

In this letter, we consider the implications of SCPV in minimal susy models for CP-asymmetries in $B \to \psi K_s$ decays. It is well known that the Standard Model predicts large CP-violation in these decays, namely $\sin 2\beta \geq 0.4$ where β is the one of the angles of the unitarity triangle [21]. Currently this CP-asymmetry is being studied experimentally by the CDF collaboration. Even though the statistics does not allow to make definite statements about the validity of the SM predictions at the moment, large CP-violation in this decay has been hinted. The purpose of this paper is to determine whether a large CP-asymmetry, $\sin 2\beta \geq 0.4$, can be explained in susy models with spontaneously broken CP.

2 CP-Asymmetry in $B \to \psi K_s$ Decay and Spontaneous CP-Violation

In this section we will consider minimal susy models with spontaneously broken CP and obtain the lower bound on the CP-violating phase as dictated by $\sin 2\beta \geq 0.4$.

It has been shown that the Next-to-Minimal Supersymmetric Standard Model (NMSSM) is the simplest susy model which allows spontaneous CP-violation while being consistent with the experimental bound on the lightest

Higgs mass [8]. In the most general version of the NMSSM with the superpotential

$$W = \lambda \hat{N} \hat{H}_1 \hat{H}_2 - \frac{k}{3} \hat{N}^3 - r\hat{N} + \mu \hat{H}_1 \hat{H}_2 + W_{fermion} \ , \qquad (1)$$

SCPV can occur already at the tree level thereby avoiding the Georgi-Pais theorem [6]. Note that even though SCPV in the MSSM is allowed theoretically [5], such a scenario is ruled out by the LEP constraints on the axion mass [7].

We will assume that *all* CP-violating effects result from the complex Higgs VEV's

$$\langle H_1^0 \rangle = v_1, \ \langle H_2^0 \rangle = v_2 e^{i\rho}, \langle N \rangle = n e^{i\xi} \ . \qquad (2)$$

The relevant interactions[1] for one generation of fermions (after spontaneous $SU(2) \times U(1)$ symmetry breaking) can be written as follows [9,12]:

$$\begin{aligned} \mathcal{L} &= -h_u H_2^0 \bar{u}_R u_L - h_d H_1^0 \bar{d}_R d_L - g \overline{\tilde{W}^c} P_L d \ \tilde{u}_L^* + h_d \bar{d} P_L \tilde{H}^c \tilde{u}_L \\ &+ h_u \overline{\tilde{H}^c} P_L d \ \tilde{u}_R^* + h.c. \ , \qquad (3) \\ \mathcal{L}_{mix} &= -g(\ v_1 \overline{\tilde{H}} P_L \tilde{W} + v_2 e^{-i\rho} \overline{\tilde{W}} P_L \tilde{H} \ ) + e^{-i\kappa_u} h_u {m_{LR}^{(u)}}^2 \tilde{u}_R^* \tilde{u}_L \\ &+ e^{-i\kappa_d} h_d {m_{LR}^{(d)}}^2 \tilde{d}_R^* \tilde{d}_L + h.c. \ , \qquad (4) \end{aligned}$$

where $h_{u,d}$ denote the Yukawa couplings and $\kappa_{u,d}$ are certain functions of the Higgs VEV phases ρ and ξ. In what follows, we assume, for the sake of definiteness, that $|\kappa_u| = |\kappa_d| = |\kappa|$, ${m_{LR}^{(u)}}^2 = {m_{LR}^{(d)}}^2 = m_{LR}^2$, and that κ and m_{LR}^2 are generation independent. Equation (4) represents the wino-higgsino and left-right squark mixings, with the former being responsible for the formation of the mass eigenstates - charginos. However, following Ref. [9], we will prefer the "weak" (wino-higgsino) basis over the mass (chargino) one.

Information about the angle β of the unitarity triangle was extracted from the decay rate evolution

$$\Gamma(B^0[\bar{B}^0](t) \to \psi K_s) \ \propto e^{-\Gamma t} \Big(1 - [+] \sin 2\beta \ \sin \Delta m t \Big) \ ,$$

[1]The complete list of interactions can be found in [12].

where Δm is the $B_L - B_H$ mass difference. On the other hand, the angles of the unitarity triangle can be expressed in terms of the mixing (ϕ_M) and decay (ϕ_D) phases which enter the $B - \bar{B}$ mixing and $b \to q\bar{q}Q$ decay diagrams. For the process under consideration,

$$\sin 2\beta = \sin(2\phi_D + \phi_M) \ . \tag{5}$$

This relation is theoretically clean since it does not involve hadronic uncertainties and can serve as a sensitive probe for physics beyond the Standard Model. At the present time, the CKM entries are not known precisely enough to make a definite prediction for β. However, it is known that $\sin 2\beta$ must fall between 0.4 and 0.9 in order for the CKM model to be consistent [21]. In our model, we will impose this condition together with Eq.(5) to obtain the lower bound on the CP-violating phases appearing in the decay and mixing diagrams.

Let us now proceed to calculating the CP-violating effects in $B - \bar{B}$ mixing. Figure 1 displays what we believe to be the most important contributions to the real part of $B - \bar{B}$ mixing. These include the Standard Model box and wino superbox diagrams. It has been argued [9] that all significant CP-violating effects result from complex phases in the propagators of the superparticles. For the $K - \bar{K}$ system, one loop diagrams involving complex phases in the wino-higgsino and left-right squark mixings can lead to the correct values of ϵ and ϵ' [9]. The analogous $B - \bar{B}$ diagrams are shown in Figure 2 (in the case of $K - \bar{K}$ mixing, the diagram in Fig. 2b is super-CKM suppressed and can be neglected). Besides the above mentioned contributions, there is a number of other contributions to $B - \bar{B}$ mixing which can be classified as follows:

1. Higgs boxes,
2. gluino superboxes,
3. neutralino superboxes.

The gluino contribution can be neglected since the gluino is likely to be very heavy: $m_{\tilde{g}} \geq 310 \ GeV$ [13]. Further, the neutralino analogs of Figs.2a,b have to involve at least two powers of h_b and, thus, are suppressed by $(m_b/m_W)^2$. The same argument applies to the charged Higgs contribution [10]. On the other hand, the neutralino and Higgs contributions to $Re \ (B - \bar{B})$ can be significant. However, they interfere with the SM contribution constructively [14] and can only reduce the $B - \bar{B}$ mixing weak phase. Since our purpose

is to determine the *lower* bound on this phase as dictated by $\sin 2\beta \geq 0.4$, we can safely omit these corrections.

Therefore, for our purposes it is sufficient to retain the SM and chargino contributions only. Furthermore, note that we may concentrate on the $(V-A)\times(V-A)$ interaction solely since 4-fermion chargino-generated interactions involving the right handed quarks are suppressed by powers of m_b/m_W. As a consequence, hadronic uncertainties and QCD corrections will not affect our results since those will cancel in the expression for the phase. The resulting 4-fermion interaction can be expressed as

$$\begin{aligned}\mathcal{O}_{\Delta B=2} &= (\ k_{SM} + k_{SUSY} + e^{i\delta} l_2 + z e^{-i\delta} l_2 + e^{2i\delta} l_4 + z^2 e^{-2i\delta} l_4\ ) \\ &\times\ \ \bar{d}\gamma^\mu P_L b\ \bar{d}\gamma^\mu P_L b\ ,\end{aligned} \tag{6}$$

where k_{SM} and k_{SUSY} are real couplings induced by the diagrams in Fig.1a and Fig.1b, respectively. The CP-violating couplings $e^{i\delta} l_2$ and $e^{2i\delta} l_4$ result from the diagrams with two and four complex mixings shown in Figs.2a and 2b, respectively ($l_{2,4}$ are defined to be real). It is important to note that along with the diagrams explicitly shown in Fig.2, there are also "cross" diagrams in which the positions of $\tilde{t}_L$ and $\tilde{t}_R$ are interchanged. Such graphs contribute with opposite phase and may seem to lead to a complete cancellation of the imaginary part of the coupling. However, this cancellation is only partial [9] owing to the fact that the higgsino vertex is, generally speaking, different from that of gaugino. Such partial cancellation is accounted for by a variable factor z ($0 \leq z \leq 1$).

The Standard Model contribution is given by [15][2]

$$k_{SM} = \frac{G_F^2}{16\pi^2} m_t^2 H(x_t)\ (V_{tb} V_{td})^2\ , \tag{7}$$

with $H(x)$ being the Inami-Lim function. To estimate the superbox contributions, we may treat the gaugino and higgsino as particles of mass $m_{\tilde{W}}$ with (perturbative) mixing given by Eq.(4). In this approximation, the chargino propagator with a mixing insertion (Fig.2) is proportional to $g(v_1 + v_2 e^{-i\rho}) \frac{m_{\tilde{W}} \not{k}}{(k^2 - m_{\tilde{W}}^2)^2}$. The resulting 4-fermion couplings are given by

$$k_{SUSY} \ = \ \frac{g^4 \zeta^2}{128\pi^2} \frac{1}{m_{\tilde{q}}^2}\ (\tilde{V}_{tb} \tilde{V}_{td})^2\ \frac{1}{(y-1)^2} \Big[y + 1 - \frac{2y}{y-1} \ln y \Big]\ , \tag{8}$$

[2] We do not show the QCD correction factor explicitly.

$$
\begin{aligned}
e^{i\delta} l_2 &= \frac{g^4 h_t^2 \zeta}{64\pi^2} \, \frac{m_{LR}^2 e^{-i\kappa} \, (v_1 + v_2 e^{-i\rho})}{m_{\tilde{q}}^5} \, (\tilde{V}_{tb} \tilde{V}_{td})^2 \\
&\times \frac{\sqrt{y}}{(y-1)^5} \left[3 - 3y^2 + (1 + 4y + y^2) \ln y \right] , \qquad (9) \\
e^{2i\delta} l_4 &= \frac{g^4 h_t^4}{384\pi^2} \, \frac{m_{LR}^4 e^{-2i\kappa} \, (v_1 + v_2 e^{-i\rho})^2}{m_{\tilde{q}}^8} \, (\tilde{V}_{tb} \tilde{V}_{td})^2 \\
&\times \frac{1}{(y-1)^7} \left[-1 - 28y + 28y^3 + y^4 - 12y(1 + 3y + y^2) \ln y \right] , \qquad (10)
\end{aligned}
$$

where $y = m_{\tilde{W}}^2 / m_{\tilde{q}}^2$; $m_{\tilde{q}}$ and $m_{\tilde{W}}$ denote the top squark and the chargino masses, respectively, and $\tilde{V}$ is the squark analog of the CKM matrix. In these considerations, the top squark contribution is believed to play the most important role. The influence of the c- and u-squarks is taken into account through a variable super-GIM cancellation factor ζ $(0 \leq \zeta \leq 1)$. Such a factor is associated with every squark line on which summation over all the up-squarks takes place. Since masses of the top and c, u-squarks are expected to be very different due to the large top Yukawa coupling (as motivated by SUGRA), the natural value of ζ would be of order unity (ζ is defined to vanish in the limit of degenerate squarks).

To derive the lower bound on the phase δ, we may replace $v_1 + v_2 e^{-i\rho}$ in Eqs.(9) and (10) by its "maximal" value $\sqrt{2} v e^{-i\rho}$ with v defined in the usual way: $v = \sqrt{v_1^2 + v_2^2} \approx 174 GeV$. Apparently, $\delta \leq |\rho| + |\kappa|$.

Let us now determine the weak phases ϕ_M and ϕ_D. It follows from Eq.(6) that

$$
\tan \phi_M = \frac{l_2 (1 - z) \, \sin \delta + l_4 (1 - z^2) \, \sin 2\delta}{k_{SM} + k_{SUSY} + l_2 (1 + z) \, \cos \delta + l_4 (1 + z^2) \, \cos 2\delta} \, . \qquad (11)
$$

On the other hand, the decay phase ϕ_D is negligibly small [10]. Indeed, in our model, the only source of CP-violation in the process $b \to c\bar{c}s$ is the superpenguin diagram with the charginos and squarks in the loop[3]. However, this diagram is greatly suppressed as compared to its CP-conserving counterpart, W mediated tree level decay, due to the loop factors and heavy squark propagators. Also, unlike for the kaon decays, there is no $\Delta I = 1/2$

[3] Another possible contributor, Higgs-mediated tree level decay, is suppressed by the quark masses.

enhancement of the $(V-A)\times(V+A)$ interactions. As a result, the weak decay phases can be neglected. This also means that direct CP-violation in our model is negligibly small as compared to that in the Standard Model (unless there is no tree level decay mode).

According to Eq.(5), the angle β is determined by

$$\sin 2\beta = \sin\phi_M \ . \tag{12}$$

Then the experimental bound $\sin 2\beta \geq 0.4$ can be translated into

$$\tan\phi_M \geq 0.44 \ . \tag{13}$$

This, in turn, leads to a lower bound on the phase δ which can be obtained numerically from Eq.(11). Note that Eq.(11) is free of hadronic uncertanties and QCD radiative corrections.

3 Numerical Results

In this section we will discuss implications of Eq.(13) and its compatibility with the upper bound on the NEDM.

It is well known that the tight experimental bound on the NEDM imposes stringent constraints on the CP-violating phases which appear in extensions of the Standard Model. In our model, the largest contributions to the NEDM are shown in Fig.3. Barring accidental cancellations, one can constrain the CP-phases entering the higgsino-gaugino and squark left-right mixings via the chargino (Fig.3b) and gluino (Fig.3a) contributions to the NEDM, respectively. Consequently, the phase δ appearing in the $B-\bar{B}$ mixing becomes bounded due to

$$\sin\delta \leq |\sin\kappa| + |\sin\rho| \ . \tag{14}$$

This requires δ to be of order 10^{-2}-10^{-1} [9,16].

On the other hand, Eq.(13) imposes a lower bound on δ. As seen from Eqs.(8)-(10), this bound depends strongly on the super-CKM matrix. We consider the following possibilities:
1. the super-CKM matrix duplicates the CKM one, $\tilde{V}_{td} \approx V_{td}$;
2. the super-CKM mixing is enhanced, $\tilde{V}_{td} \approx V_{td}/\sin\theta_C$;
3. the super-CKM mixing is doubly enhanced, $\tilde{V}_{td} \approx V_{td}/(\sin\theta_C)^2$.

In all of these cases we assume $\tilde{V}_{tb} \sim 1$. The first possibility implies that the supersymmetric contribution to $B-\bar{B}$ mixing is suppressed as compared to the CP-conserving Standard Model box diagram. As a result, we find that the constraint $\tan\phi_M \geq 0.44$ cannot be satisfied for any δ even assuming light ($100\ GeV$) squarks. For the same reason, we are bound to consider only light ($100\ GeV$) chargino and maximal left-right squark mixing, $m_{LR} = m_{\tilde{q}}$. On the other hand, the third option is unrealistic since it leads to an unacceptably large stop contribution to the $K_S - K_L$ mass difference unless the top squark mass is around $1\ TeV$. Therefore, we are left with the second possibility which we will examine in detail. From now on we assume that $\tilde{V}_{td} \simeq V_{td}/\sin\theta_C,\ m_{\tilde{W}} \simeq 100GeV,\ m_{LR} \simeq m_{\tilde{q}}$, and will study the behavior of the lower bound on δ as a function of the remaining free parameters - $z, \zeta, \tan\beta$, and $m_{\tilde{q}}$.

Fig.4 displays a typical picture showing inconsistency of the model.[4] The lower bound exceeds the upper bound by one or two orders of magnitude. Moreover, the region allowed by the CP-asymmetry in $B \to \psi K_S$ is restricted to the left upper corner of the plot. The reason for that can be easily understood. Indeed, if the squarks are heavy, the magnitude of the susy contribution is negligible as compared to that of the CP-conserving SM box and sufficient CP-violation cannot be produced regardless of how large the phases are.

Let us now consider the effect of each of the variable parameters.[5]

1. $\zeta - dependence\ (Fig.5)$.
The lower bound on δ relaxes as we introduce the super-GIM cancellation. This occurs due to the increasing share of the CP-violating diagram in Fig.2b. However, theoretically one expects ζ to be of order unity due a large difference between the stop and other squarks masses.

2. $\tan\beta - dependence\ (Fig.6)$.
The gap between the lower and upper bounds widens drastically as $\tan\beta$ increases. Recalling that $h_u = \frac{g m_u}{\sqrt{2} m_W \sin\beta}$ and $h_d = \frac{g m_d}{\sqrt{2} m_W \cos\beta}$, it is easy to see

[4]The displayed bound on the NEDM was calculated for the gluino mass in the range $300 - 500\ GeV$ using the standard formulas [16].

[5] We are assuming that δ belongs to the second quarter. Even stricter lower bounds on $\sin\delta$ can be obtained for δ in the second quarter due to a partial cancellation in the numerator of Eq.(11).

that for large $\tan\beta$ the NEDM constraint becomes stricter due to the large h_d whereas the CP-violating contributions to $B-\bar{B}$ mixing, proportional to powers of h_t, decrease. We do not consider the case $\tan\beta < 1$ because of the SUGRA constraints and the breakdown of perturbation theory in this region.

3. $z - dependence$ $(Fig.7)$.
Apparently, the incorporation of a partial cancellation ($z > 0$) among the CP-violationg contributions makes the lower bound rise. One expects the natural value for z to be around 1/2.

In all of these cases the regions allowed by the NEDM and $B \to \psi K_S$ are at least an order of magnitude apart.[6] Furthermore, heavy squarks ($\geq 400\ GeV$) are prohibited by large CP-asymmetries observed in $B \to \psi K_S$. This condition is quite restrictive and may alone be sufficient to rule out the model in the near future (even if large CP-phases were allowed).

It should be mentioned that, in the limit of large $\tan\beta$, the CP-violating neutralino and Higgs contributions to $B-\bar{B}$ mixing become more important. However, the CP-phases are severely constrained in this case ($\sim 10^{-3}$). Therefore, these contributions do not lead to any considerable modifications of our analysis.

4 Further Discussion

The model under consideration has further implications for B-physics. For instance, in this model, direct CP-violation is greatly suppressed in all tree-level allowed processes as compared to what one expects in the Standard Model. This provides another signature testable in the near future.

The other angles of the unitarity triangle, α and γ, can be determined in a similar manner from, for example, $B_d \to \pi^+\pi^-$ and $B_s \to \rho K_s$ decays [11]. However, in the Standard Model, one cannot determine these angles from the decay rate evolution and relations analogous to (5) precisely enough due to considerable penguin contributions. To eliminate their influence, one can use isospin and $SU(3)$ relations [18]. For instance, in order to determine α, one needs to know the rates of $B_d \to \pi^+\pi^-$, $B_d \to \pi^0\pi^0$, and $B_d^+ \to \pi^+\pi^0$

[6] Note also that small CP-phases are disfavored by the bound on the lightest Higgs mass [8].

along with the rates of their charge conjugated processes. Then α can be found from certain triangle relations among the corresponding amplitudes. In our case, however, this analysis becomes trivial due to a vanishingly small interference between the tree and superpenguin contributions. As a result, α can be read off directly from the analog of Eq.(12). The angles extracted in such a way normally do not exceed a few degrees (modulo 180^0) and do not form a triangle [10].

In our model, the angles of the unitarity triangle do not have a process-independent meaning. Indeed, contrary to the Standard Model, they cannot be extracted from direct CP-violating processes simply because such processes are prohibited. Moreover, these angles are not related to the sides of the unitarity triangle.

Another important consequence of the model is that the CKM matrix is real and orthogonal. This, of course, is also true for general (nonsupersymmetric) two Higgs doublet models with FCNC constraints, in which CP is broken spontaneously [19]. As a result, $|V_{ub}|$, $|V_{td}|$, and $|\sin\theta_C V_{cb}|$ must form a flat triangle. Presently, such a triangle is experimentally allowed provided new physics contributes significantly to Δm_{B_d} [20]. To determine the status of these models, a more precise determination of $|V_{ub}|$ and $|V_{td}|$ is necessary. Orthogonality relations among other CKM entries are less suitable for probing this class of models due to the small CKM-phases involved.

We have considered in detail the case of the NMSSM. The results, however, remain valid for NMSSM-like models with an arbitrary number of sterile superfields $\hat{N}$. Indeed, since the $\hat{N}$'s do not interact with matter fields directly, an introduction of a sterile superfield does not affect the way CP-phases enter the observables. The CP-violating effects will still be described by the diagrams in Figs.2 and 3. Therefore, the argument we used also applies to this more general situation: the CP-phase in left-right squark mixing can be constrained via the gluino contribution to the NEDM, whereas the phase in the gaugino-higgsino mixing can be constrained via that of the chargino (assuming no accidental cancellation). In the same way, we find that the lower and upper bounds on the CP-phases are incompatible. A nontrivial extension of the model, in which a cancellation among various contributions to the NEDM can be well motivated, is necessary to rectify this problem. [7]

[7] The possibility of such a cancellation in certain susy models has recently been considered by a few authors. It is, however, unclear whether this cancellation can be made

5 Conclusions

We have analyzed the CP-asymmetry in $B \to \psi K_s$ decay within minimal supersymmetric models with spontaneous CP-violation. We have found that the CP-asymmetry required by $\sin 2\beta \geq 0.4$ can be accommodated in these models only if the following conditions are met:
1. left-right squark mixing is maximal, $m_{LR} \simeq m_{\tilde{q}}$,
2. super-CKM mixing is enhanced, $\tilde{V}_{td} \simeq V_{td}/\sin\theta_C$,
3. the chargino is relatively light, $m_{\tilde{W}} \simeq 100\, GeV$,
4. the t-squark is lighter than $350 - 400\, GeV$.

Even if this is the case, the required CP-violating phases are larger than those allowed by the bound on the NEDM by one or two orders of magnitude.

We conclude that the model under consideration cannot accommodate a large CP-asymmetry in $B \to \psi K_s$ while complying with the bound on the NEDM. Thus, if the Standard Model prediction gets confirmed, the model will be recognized unrealistic. The result holds true for models with an arbitrary number of sterile superfields. To reconcile theory with experiment one would have to resort to essentially nonminimal scenarios in which large CP-violating phases are naturally allowed.

Note also that since, in this approach, CP-violation is a purely supersymmetric effect, the model requires the existence of a relatively light t-squark. This may conflict with the Tevatron constraints on supersymmetry in the near future (see, for example, [13]).

We have also discussed other testable predictions of the model. Among them are the suppression of direct CP-violation and orthogonality of the CKM matrix.

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natural (see [17] and references therein).

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Figure Captions

Fig. 1a,b Most important contributions to $B - \bar{B}$ mixing.

Fig. 2a,b Dominant CP-violating contributions to $B - \bar{B}$ mixing (all possible permutations are implied).

Fig. 3a,b Contributions to the NEDM allowing to constrain the wino-higgsino and squark left-right mixing phases.

Fig. 4 Regions allowed by the CP-asymmetry in $B \to \psi K_s$ (upper) and the bound on the NEDM (lower). Typically, the region allowed by $B \to \psi K_s$ is much smaller than shown here due to the partial cancellation (see Fig.7, $z = 1/2$).

Fig. 5 Lower bound on $\sin\delta$ as a function of the super-GIM cancellation parameter ζ: 1 - $\zeta = 1$, 2 - $\zeta = 1/2$, 3 - $\zeta = 1/4$.

Fig. 6 Lower bound on $\sin\delta$ as a function of $\tan\beta$: 1 - $\tan\beta = 1$, 2 - $\tan\beta = 25$.

Fig. 7 Lower bound on $\sin\delta$ as a function of the partial cancellation parameter z: 1 - $z = 0$, 2 - $z = 1/4$, 3 - $z = 1/2$.